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Impact of Duty Cycle on Wear Progression in Variable-displacement Vane Oil Pumps

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Abstract

Variable-displacement vane oil pumps are increasingly employed in automotive powertrains for their efficiency benefits through reduced losses. However, confirming long life reliability of a new commodity based on limited data available from product development tests and early field experience is a significant challenge, which is addressed by the work presented in this paper. The approach presented combines physical examination of pumps returned from tests, with analysis of damage factors for pump wear progression, and an analysis of functional parameters for the powertrain system focused on the cause effect linkages across the systems hierarchy. The metrology results from physical measurements of used parts provide useful insights for the wear progression and the expected service performance of the pump. The paper also expands towards a data driven approach based on ECU data analysis that could provide a pathway towards the development of online health monitoring and diagnostics of the oil pumps.

Keywords: vane oil pump, wear, degradation assessment, diagnostics, life prediction modelling

1. Introduction

The function of an engine lubrication system is to distribute the oil to all moving parts in order to reduce friction and remove surplus heat from the engine. Oil pump, often referred to as the *heart* of an engine, plays a crucial role in this process by ensuring the supply of lubricant at the required flowrates. Any failure or performance degradation in

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the oil pump can have severe impact and may cause long-lasting damage to the engine, therefore oil pump reliability and robustness are prime design factors for engine design.

In conventional fixed-displacement oil pumps, oil flow delivery is directly proportional to engine speed. In order to ensure sufficient oil supply at low engine speeds, the pumps are inevitably oversized and, by implication, they are inherently inefficient as they generate excess flow at higher engine speeds. This contributes to engine power losses and also results in higher oil degradation rates. In contrast, variable-displacement oil pumps allow for optimal control of the oil flow to match the engine demands. In case of vane oil pumps, this is achieved by using a solenoid to actuate a variable eccentricity between the cam ring and the rotor [1]. Hence, the volume of the pump itself, and thus the oil flow supply, can be dynamically adapted in relation to the engine oil pressure demand [2].

While vane oil pumps are known for a long time, their adoption for automotive applications is relatively new. However, given the benefit of improved efficiency, which translates directly to fuel economy supporting achievement of increasingly stringent environmental standards and customer demand, they have become common choice. Arata et al. [3] argued that vane oil pumps may become a standard in the future due to their significantly reduced driving torque. It has also been shown that in particular under cold engine conditions, the starting torque required for these types of pumps is at least 4 times less compared to fixed displacement pumps. Mancò et al. [4], based on a combined simulation and experimental study of efficiency, concluded that variable-displacement vane pumps allow for attainment of torque saving of more than double compared to the variable flow geo-rotor pumps.

However, as with all mechanical devices, pumps are subject to aging and wear, which tends to degrade performance and reduce engine efficiency due to increased negative torque. Conventional fixed displacement pumps have proven durability in automotive applications. In contrast, the evidence for the reliability of variable displacement vane oil pumps is relatively scarce in relation to highly varied duty cycles and environmental conditions that can be expected in an automotive engine application. From the perspective of an OEM, validation of high mileage / long life reliability of a new design solution for a commodity such as an oil pump for a new engine application based on data available from the product development test and early service experience, is of significant importance.

The work presented in this paper is underpinned by a data driven approach to life prediction methodology of automotive systems. The scope of the work presented herein is a variable displacement vane oil pump used within a family of engine applications, for which limited data from early product development and service life is available. From an engineering viewpoint, the first objective of the case study is to evaluate whether early durability test data provide signs of potential concerns for the high mileage vehicle life stage. Furthermore, the linkage between physical degradation and specific drive cycles is of particular interest for the derivation of a life prediction modelling, and the feasibility of implementing on-line diagnostics for the oil pump state of health is a further research objective.

The organization of the paper is as follows: section 2 provides a review of state of art literature on automotive oil pumps; section 3 describes the experimental methodology, section 4 introduces results of degradation analysis, ECU data analysis is presented in section 5 followed by conclusions in section 6.

2. Overview of related literature

Various aspects of vane oil pumps have been extensively studied, including impact of vane geometry on driving torque [5], examination of friction reduction between vane tip and cam ring in [6], and choosing optimal vane spacing [7]. While full description of mechanical characteristics, including wear and degradation, would require measurement of forces inside the pump, this is not practically feasible. Alternatively, Sullivan and Sehmby [8] described a simulation approach to establish internal forces with respect to rotational speed ranges, while Xia [9] conducted vibration analysis to detect faulty oil pumps. Pump power losses studies have been reported in [10, 11] based on numerical and experimental tests, which have shown variation in the flow due to changes in the temperature and pressure, which could be linked to internal leakages between chambers, which can be significant at high oil temperatures . It has also been observed that friction occurs primarily between vane tip and cam ring, but also between rotor sides and housing, vane sides and housing, vane side and slot of inner rotor, cam ring and housing. Powel loss was reported in relation to incomplete chamber filling caused by high speeds or due to excessive presence of air, known as cavitation and aeration.

According to Staley et al. [12] the energy required for driving engine oil pump results in up to 2.5% of total vehicle fuel consumption, while Arata et al. [3] estimates even 3% for ordinary engines. Considering that some torque will be still required to drive the pump, improvements in the range from 0.5% to 2% should be achievable for optimally controlled oil pumps.

While it is known that wear progression can also reduce pump efficiency, such studies have not been widely reported for this types of pumps. This paper aims to carry out degradation analysis of pumps from early life engine tests and service data to evaluate the impact of duty cycle on wear rate. This knowledge may later find application in health assessment technologies and life prediction modelling approaches. Life prediction model combines both, degradation analytical model and specific patterns from historical usage behavior [13]. Generic analytical models are obtained during testing approaches, e.g. as described by Wei et al. [14]. However, such models are based on testing results carried out in specific well controlled conditions and do not necessarily reflect real world usage variations. Considering duty cycle may allow to improve prediction model accuracy and support further prognostics.

3. Methodology

Degradation analysis requires well-equipped facilities to conduct specific component tests under controlled conditions. In the context of this study, however, such data was not available. Instead, this study relied on data available from product development engine tests and early vehicle tests, for which full test history (as load cycle and engine ECU data) was logged, and parts were available to inspect after the test.

As summarized in Table 1, 15 oil pumps (schematically illustrated in Fig. 1) were available for the study. Pumps labelled 1-7 were available field test vehicles with varying duty cycles, labelled cycle 1 - 4, including combinations of motorway, countryside and city driving. Three pumps, labelled 8-10, came from engine dynamometer durability testing, with duty cycles labelled 5-7. For the purpose of comparison, in order to evaluate wear and degradation trends, 5 brand new ("green") pumps were also included in the study.

Table 1. List of oil pumps available for study

Pump Number	Mileage (km/hours)	Cycle
New (Green) – 5 pumps	0	N/A
Pump 1	10720	Cycle 1
Pump 2	32180	Cycle 2
Pump 3	54706	Cycle 2
Pump 4	56315	Cycle 3
Pump 5	98104	Cycle 3
Pump 6	102976	Cycle 3
Pump 7	112630	Cycle 4
Pump 8	Dyno: 40 hours	Cycle 5
Pump 9	Dyno: 80 hours	Cycle 6
Pump 10	Dyno: 325 hours	Cycle 7

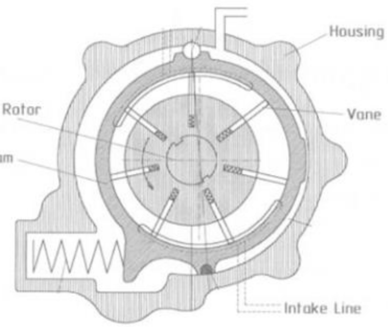

Fig. 1. Vane oil pump schematics [15]

In order to carry out a reliability assessment addressing the research objectives outlined in section 1 of the paper, the following studies have been included in the plan:

1. Wear and degradation analysis of used pumps to evaluate signs of wear and degradation that can lead to performance loss. For degradation analysis, the pumps returned from field or test, were dismantled, carefully cleaned from oil, and measured using Talysuf and Leitz Reference high precision machines for key reference geometry dimensions of the component parts (in particular the vanes and cam ring which have been identified from literature as primary sites for friction and hence wear). The green pumps were also measured.
2. Damage factors and parameters mapping, to establish the cause-effect linkage between system (engine) operating attributes / parameters and the failure mechanisms of the studied component (oil pump).
3. Functional parameters mapping to establish cause – effect linkages between the functional performance of the component and the functional performance of the system (engine, vehicle), which could be assessed via the logged diagnostics and ECU data available at system level.

The following subsections describe the methodology used for tasks 2 and 3.

3.1. Damage parameters mapping

To understand oil pump fatigue and wear mechanisms, it is important we identify and study factors influencing degradation. According to Sullivan and Sehmby [8], high engine speeds tend to produce bigger internal forces. Bigger eccentricity levels have the same effect although not as significant. Both these factors may therefore contribute to the raise in degradation rates. Friction between vane tip and ring surface is a source of efficiency loss; smoother surfaces allow hydrodynamic lubrication where oil film helps avoid metal to metal contact, hence minimizing friction. Findings from [6] confirm 5% improvement in friction torque for an average surface roughness (Rz) between 0.8 µm and 0.4 µm. Oil contamination, including soot and dilution levels, is yet another important factor to be considered; Salehi et al. [16] investigated the effects of soot on wear and friction of vane pumps, concluding that the aging of engine oil leads to increased damage on vanes. In particular, severe wear has been associated with carbon black (CB) particles. The impact of aeration and cavitation should not be underestimated as they also affect internal pressure forces and play a significant role in pump performance degradation [11]. Oil temperature has an enormous impact on the viscosity level and therefore influences oil leakages between chambers [10]. Underpinned by this discussion, Fig. 2 provides a summary of damage sources associated with pump wear.

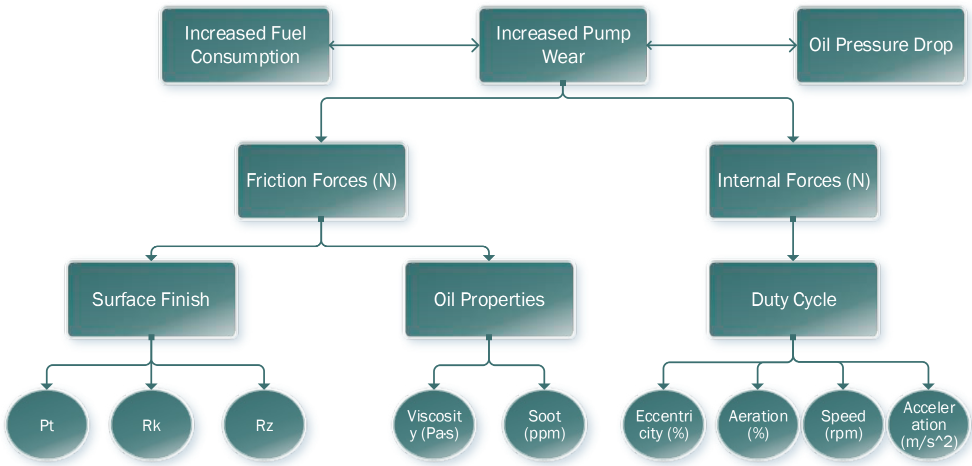

Fig. 2. Damage factors causing pump wear

3.2 Functional parameters mapping

Fig. 3 illustrates the functional relationship between oil pump wear and functional parameters across different hierarchical system levels. The diagram in Fig. 3 captures the association between measurable attributes of the operational states (available from ECU data) and the cause-effect links with the physical state of the oil pump (i.e. in terms of geometry of pump parts, which are affected by wear and degradation incurred by usage). Wear on vanes and cam ring (assessed through metrology measurements / data) results in decreased oil pump efficiency. From lubrication system perspective, this is likely to result in gallery oil pressure drop (monitored by ECU data). The electronic control system of the pump will seek to compensate for the oil pressure drop by adjusting the solenoid position to increase the oil flow rate; the current drawn by the solenoid is an ECU recorded parameter. However, in order to do so, degraded pump needs to work harder, which will impose additional negative torque on engine, which could result in increased fuel consumption, and possible fault codes, which, from diagnostics point of view, may provide a fingerprint in the warranty records, normally perceived as a “symptom”.

The analysis of the causal links within the functional parameter mapping can be employed to establish online diagnostics and health monitoring methods for the oil pump.

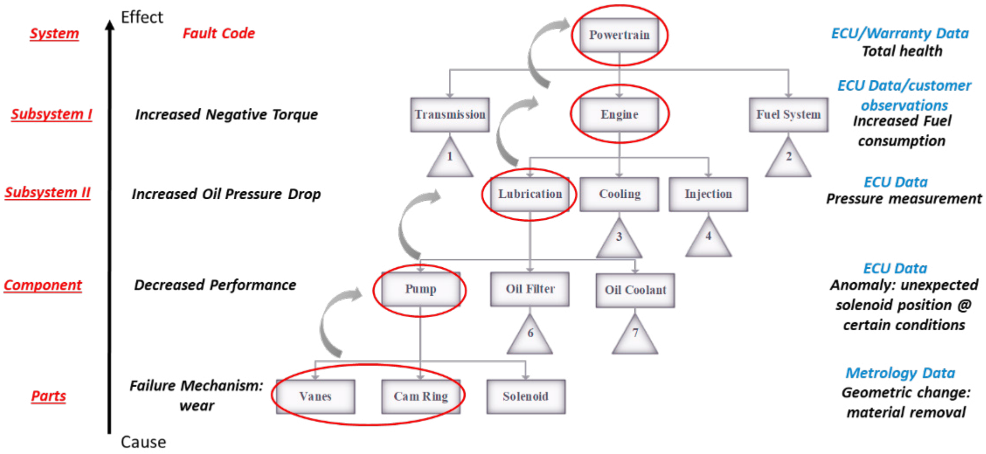

Fig. 3. Oil pump functional mapping

4. Results: Oil pump degradation analysis

This section provides a summary of metrology data analysis to visualize trends in wear. Although there are only 10 used pumps, taking into account that each pump has 7 vanes, and each part was measured at several different sites, this provided a reasonably large sample of measurements. Fig. 4 and Fig. 5 depict variations of vane width measurements corresponding to each pump and test / duty cycle history (separate for field test and engine dynamometer tests), as listed in Table 1. For both figures, the green leftmost boxplot summarizes the reference measurements from the 5 new pumps. While there are obvious differences observed between summarized measurement data from different pumps even from the same duty cycle, which don't immediately correlate with mileage, none of the measured pumps showed excessive wear in relation to vane width. Results from the pumps from engines on dynamometer tests show a more consistent pattern of increased vane width, however, the sample size is too small to allow quantitative analysis.

Fig. 6 illustrates 3D plots of a vane flatness measurement. It is evident that the vane is becoming thinner in the middle and thicker by the sides, an observation that is consistent across all measured vanes / samples. A scatter plot of deviation in average vane flatness reveals a positive correlation with mileage, as shown in Fig. 7. Two possible "outliers" (circled) were observed, which could point that it may be more reasonable to plot data against number of cycles rather than mileage.

Previously, it had been discussed that vane tip surface roughness has direct impact on pump efficiency. According to measurements (Fig. 8), even after 100k kilometers there is an apparent slight improvement in surface roughness, i.e. effect of polishing is present. Exception is cycle 4 that shows a more significant deterioration. Measurements of the internal ring (Fig. 9) also highlights cycle 4 as out of trend, while the rest do not have any significant wear observed.

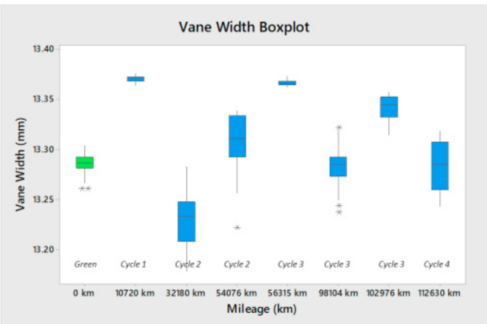

Fig. 4. Vane width vs. mileage

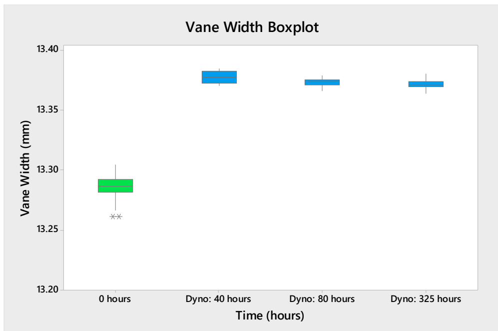

Fig. 5. Vane width vs. hours (dyno)

There are almost no changes in either cam ring roundness or internal diameter, with the exception of cycle 4. Some significant change in roundness can be observed (Fig. 10) for cycle 4 – which also has the highest mileage. Similar observation was made in relation to vane rings measurements; the outer diameter (Fig. 11) became 0.2 mm smaller as a result of adhesive wear and there is also deterioration in roundness.

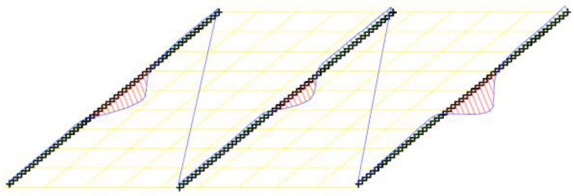

Fig. 6. Vane flatness 3D plot

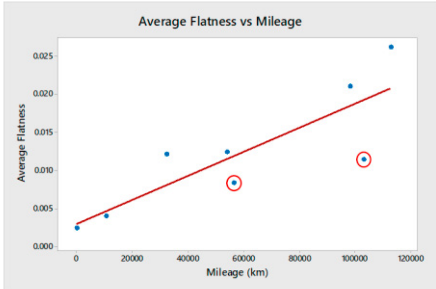

Fig. 7. Vane flatness vs. mileage

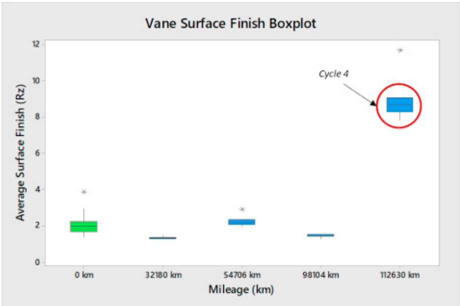

Fig. 8. Vane tip average surface roughness (Rz)

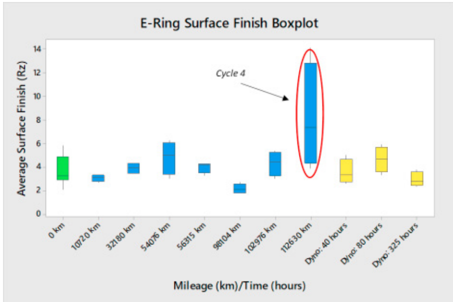

Fig. 9. Cam Ring Average Surface Roughness (Rz)

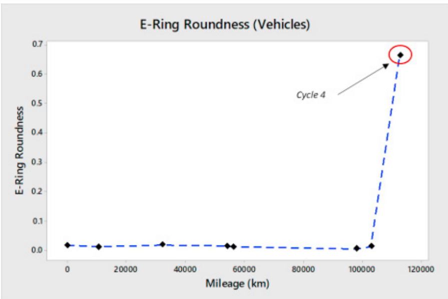

Fig. 10. Cam Ring Roundness vs. Mileage

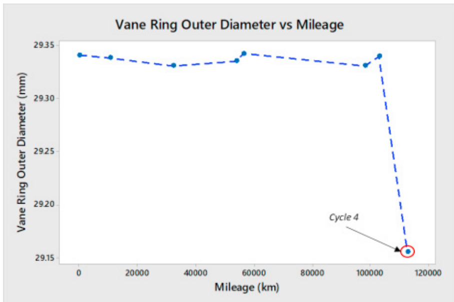

Fig. 11. Vane Ring Outer Diameter vs. Mileage

5. Outline methodology for online pump diagnostics

5.1. Damage Cycle Count based on ECU Data Analysis

The results in previous section clearly show that mileage is not the best indicator for oil pump health. Load cycles count would be a more accurate variable for life prediction modelling. The damage factors analysis in Fig. 2 indicates that engine speed is one of the factors that quantifies the duty cycle, and this can be accessed from the recorded ECU data available from the vehicles on test. We have specifically aimed to analyse the difference between Cycle 4 and the other cycles referenced in Table 1. The results showed that the average engine speed for Cycle 4 is in fact significantly higher compared to other cycles. Fig. 12, for instance, illustrates the distribution of engine speed for two cycles, namely Cycles 3 and 4, showing that the average speed for Cycle 4 is about 1000 rpm higher. In fact 10% of engine speed observations are higher than 4800 rpm. This, together with consistently high vehicle travel velocity observed from the ECU data, confirmed that Cycle 4 best matches an aggressive motorway driving cycle. In contrast, the 75th percentile of engine speed for Cycle 3 is around 2000 rpm, hence much economical driving profile. The higher wear observed through measurements on pumps that have been exposed to cycle 4 indicate a higher damage rate associated with high engine speed operation. As discussed in the literature review section, high engine speeds can result in oil aeration which is also related to oil pump damage. However, the limited data sample available did not allow for a full life prediction model to be established.

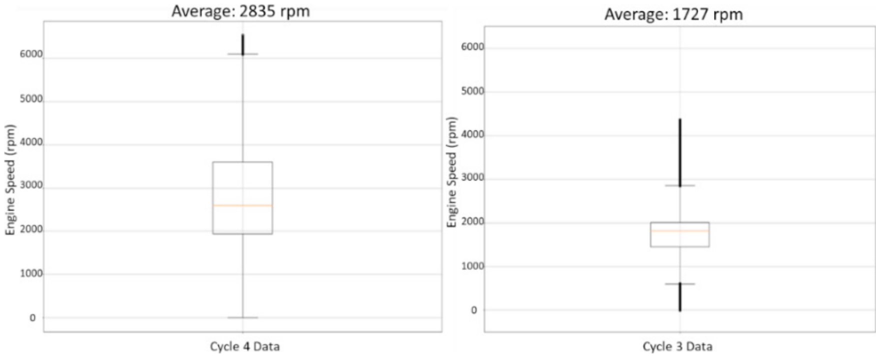

Fig. 12. Engine Speed: Cycle 4 vs. Cycle 3

5.2. Outline methodology for online pump health monitoring

Oil pump wear cannot be measured online but changes in performance may be assumed as one of key factors for damage detection [17]. The powertrain functional parameters map associated with the oil pump illustrated in Fig. 2 prompts to changes in performance that can be gauged through online measurements, available through the ECU data. Based on the joint analysis from Figures 2 and 3, parameters available in the ECU that can be related to oil pump performance and degradation through wear progression, include oil pressure (measured both at pump outlet and in the oil gallery), oil temperature, engine speed (directly proportional to pump speed) and oil pump solenoid position (which controls eccentricity which gives the volume of the pumping chamber). The solenoid position, which in Fig. 3 is at the lowest level at which a measurable parameters is available above the pump geometrical conditions which actually reflect the state of wear, is in turn controlled (as closed loop control) by ECU based on pre-calibrated maps linked to the oil pressure demanded for the specific driving conditions. Therefore, by monitoring the solenoid position for reference driving conditions (in relation to engine speed, load, oil temperature, and pressure) over time could provide an indication of the physical state of health of the pump in relation to the wear failure mechanism.

There are however several difficulties to be overcome with this strategy for health monitoring which include: (i) robust identification of similar driving conditions – which is often difficult given the ubiquitous stochastic nature of factors that affect driving conditions; and (ii) there are a number of other uncertainty factors that can affect the oil pressure, which is the key parameter in the closed loop control system for the solenoid position.

Furthermore, oil pressure depends on oil viscosity and pump speed. Oil viscosity varies with temperature and contamination level (dilution, soot, etc). Current on-board diagnostics does not provide viscosity and contamination parameters, so oil temperature remains to the only option for approximate oil condition assessment. Further work – as a combination of modelling and experimental and data driven methods (i.e. machine learning) are needed to develop and validate an online health monitoring solution.

6. Conclusions

This paper has introduced an approach to life prediction modelling of a variable displacement vane oil pump based on limited data available from product development and early service experience. The approach combines physical examination of pumps returned from tests with known history, with analysis of damage factors for oil pump wear, and an analysis of functional parameters for the powertrain system to which the pump is part of. While the physical test data is not sufficient to derive and validate a full life prediction model (as a stochastic damage accumulation model) for the oil pump, some important observations were made about wear progression for the key functional pump components. This includes the fact that with usage, the vanes become thinner in the middle and thicker by the sides, with a reasonable linear correlation observed against mileage accumulation. While there is no evidence that this sort of wear affects pump performance, it may later result in vane high cycle fatigue. Another important observation is that aggressive motorway duty cycle produced by far the highest damage observed, across on all pump parts measured. So, high engine speeds, producing bigger internal forces as well as causing oil aeration, have an observable effect on pump degradation.

Underpinned by the pump wear damage parameters mapping and the powertrain functional mapping, focused on the cause effect linkages across the systems hierarchy, the paper also expanded on the use of data driven approaches for the pump degradation prediction and online health monitoring, based on ECU data analysis. This is an important direction for further work towards the development of an intelligent online health monitoring and diagnostics.

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